Single-mode Semiconductor Reference Oscillator Development for Coherent Detection Optical Remote Sensing Applications

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Abstract-**High power single mode, tunable, narrow linewidth semiconductor lasers in the 2.05-μm wavelength region are needed for coherent detection optical remote sensing applications. 2.05-μm Fabry Perot (FP) and distributed feedback (DFB) ridge waveguide lasers fabricated from epitaxially grown InGaAsSb/AlGaAsSb/GaSb and InGaAs/InP hetero-structures are reported. This work is part of a NASA Earth Science Enterprise Advanced Technology Initiatives Program research effort to develop semiconductor laser reference oscillators for optical remote sensing from Earth orbit. In particular, local oscillators provide the frequency reference required for active spaceborne optical remote sensing concepts that use heterodyne (coherent) detection. The two most prominent Earth observation applications for this technology are Doppler LIDAR wind sensing and tropospheric carbon dioxide measurement by laser absorption spectrometry, the currently favored operational wavelength for both of which is 2.05 μm. Frequency-agile local oscillator (FALO) technology is critical in such applications because of the need to compensate for large platform-induced Doppler components that would otherwise compromise data reduction and interpretation. The semiconductor laser-based FALO option offers considerable scope for reduced mechanical complexity and improved frequency agility over equivalent crystal laser devices, while their potentially faster tuning ability holds significant potential for enhanced scanning versatility. To realize narrow linewidth operation in monolithic laser structures at the wavelength of interest at the high currents and output powers required for operation in an optical heterodyne receiver corrugation pitch-modulated distributed feedback (CPM-DFB) configuration is used. CPM-DFB lasers achieve narrow linewidth operation by suppressing gain nonlinearities inside the laser cavity that lead to linewidth re-broadening. CPM-DFB lasers utilize a grating segment of slightly different pitch to achieve added uniform light intensity along the laser cavity. CPM-DFB ridge waveguide lasers have been fabricated from InGaAs/InGaAs/InP material and hybrid external cavity distributed Bragg reflector (DBR) from InGaAsSb/AlGaAsSb/GaSb operating at a wavelength of 1.55 μm and 2.06-μm.**

I-Introduction

The coherent Doppler lidar approach for acquiring global profilometry of tropospheric winds from Earth orbit is reliant on off-nadir beam scanning geometry for retrieval of vector winds by Doppler analysis of laser radiation backscattered by entrained aerosols and cloud particles [1]. The off-nadir scan pattern induces large platform-induced Doppler components that may be compensated by scan-synchronous tuning of a frequency-agile local oscillator (LO) laser. Frequency-agile LO technology development has thus far implicitly assumed the same laser material as the transmitter laser. (The currently favored spectral region for conducting Doppler lidar wind sounding is ~2.05 μm, the operating wavelength of Tm,Ho:YLF.)

This approach has been under development for a number of years and has demonstrated functionality in a breadboard system close to that required for the space-based implementation [2-7]. However, compared to diode laser technology such devices are mechanically complex, with tuning stability and reproducibility being critically dependent on the maintenance of stringent alignment tolerances. An alternative monolithic semiconductor laser reference oscillator would offer superior resistance to environmentally induced alignment degradation and generally longer lifetime. In addition, the semiconductor laser option has the potential for considerably more rapid tuning capability, rendering feasible a wider variety of lidar pointing/scanning strategies.

The fabrication and validation of prototype novel architecture semiconductor lasers is presently under way at the Jet Propulsion Laboratory (JPL) with the express goal of addressing the power and spectral purity requirements of spacebased coherent Doppler lidar wind measurement and laser absorption spectrometry for global CO_2 mapping [8].

This technology development program has followed parallel paths involving two promising laser material systems: InGaAsP/InP and AlGaAsSb/InGaAsSb/GaSb. This approach was adopted for risk reduction purposes. These two material systems and their fundamental characteristics were described previously [9].

II. NARROW LINEWIDTH DEVICE

Although the linewidth of Fabry-Perot (FP) multimode semiconductor lasers has typically been on the order of 20 - 100 MHz., different approaches discussed in literature such as Distributed Bragg Reflector (DBR) and Distributed Feedback (DFB) lasers have been utilized in facilitating single mode selection and reducing linewidth to near 1 MHz. Unfortunately, linewidth rebroadening at relatively low optical power levels limits the use of these types of lasers in many applications. These lasers exhibit several gain non-linearities that contribute to gain and refractive index change causing power dependent single mode instability and linewidth rebroadening. To realize high single mode output power and narrow spectral linewidth <1 MHz, it is necessary to suppress longitudinal spatial hole burning (LSHB) and to optimize the optical and electrical confinement properties of carriers in a relatively long cavity. For this technology development effort the corrugation pitch-modulation (CPM) approach was selected [10]. This arrangement utilizes a dephased central grating section to prevent intensity peaking in the center of the cavity, thus suppressing the longitudinal spatial hole burning that gives rise to power broadening in semiconductor laser devices. The CPM-DFB grating concept is depicted schematically in Figure 1.

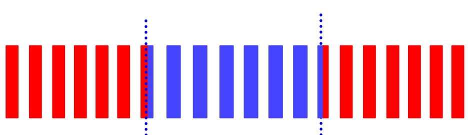


Fig. 1. Diagrammatic representation of the CPM-DFB grating concept.

The grating is designed such that each of the three sections comprises an equal number of periods, N, but the length of the center section L_2 is longer than the flanking sections ($L_1 = L_3$) by one half-period ($\Lambda_1 = \Lambda_3$). The proper implementation of a slightly different pitch segment and its relationship to other segments of the long grating is critical in achieving full control over light generation and propagation inside the laser cavity. The elimination of stitching error while maintaining the high resolution and coherency is also vital for fabricating long varied-line-spacing (i.e., λ/4–phase shifted, CPM) gratings. High quality, very long varied-line-spacing grating patterns such as uniform , λ/4-phase shifted and CPM have been fabricated side-by-side on the surface of the separate confinement hetero-structure (SCH) epitaxial layer in the 1.55 and 2-μm wavelength region using JEOL JBX-9300FS electron beam lithography system. Side-by-side integration of different type of grating patterns enables us to assess the linewidth rebroadening due to spatial hole burning in devices with similar laser multi quantum well (MQW) gain structures.

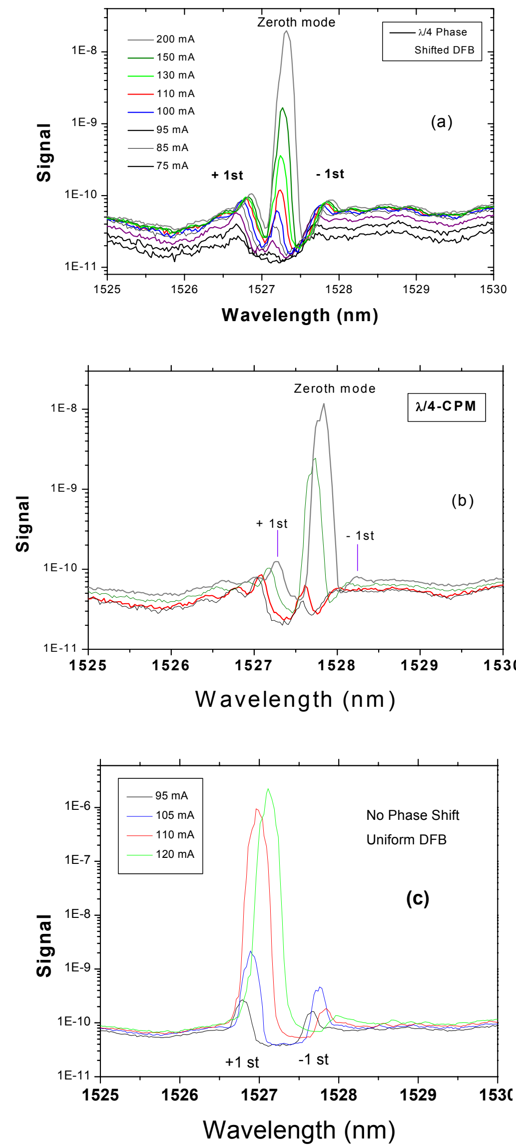


Fig. 2. Mode structure of 1.53-μm (a) l/4-phase shift, (b) l/4 –CPM and uniform DFB- RWGLD lasers fabricated next to each other on the same bar.

Results recently obtained for RWG-lasers in the 1.55 and 2.06-μm wavelength range are promising. The mode structure of λ/4-phase shifted, CPM and uniform RWG DFB lasers with 1.5 mm long cavity and 3 μm ridge width are shown in Fig. 2. These measurements were done using a double-monochrometer spectrum analyzer. This instrument enables us to measure the wavelengths of the main mode (zeroth mode), neighboring submodes (+1st and –1st modes) and the relationship between these wavelengths and driving currents in 1.55 µm wavelength region.

Spectra of a fabricated λ/4 phase shifted DFB laser that is shown for driving current up to 200 mA in Fig 2 (a) conforms well with the expected theoretical single mode operation at the Bragg wavelength (Zeroth mode) for λ/4 phase shifted DFB laser. It is clear from the spectrum for near threshold current (I_{th}) that the laser starts operating at the Bragg wavelength and maintains stable single mode operation for drive currents up to 200 mA with side mode suppression ratio (SMRS) of greater than 35 dBm. The same stable single mode operation was observed for fabricated CPM-DFB lasers as shown in Fig. 2 (b). For drive currents slightly above I_{th} and up to 200 mA the CPM-DFB laser also operates at the Bragg wavelength similar to a standard λ/4 phase shifted DFB laser shown in part (a). Even at highest currents, 200mA, the main mode remains near the center of neighboring submodes indicating suppression of spatial hole burning in the center of laser cavity. This demonstrates not only proper implementation of CPM structure with a middle segment with a slightly different pitch from other segments in order to achieve a distributed λ/4 phase shift, but also successfully demonstrate multi-segment gratings free of stitching errors while maintaining high resolution and coherency.

Spectra of a conventional uniform DFB laser is shown for driving currents near I_{th} in figure 2(c). Here, the degenerate bimodal behavior has been suppressed by different facet reflectivities. As expected, conventional uniform DFB lasers, do not show laser operation at the Bragg wavelength but they operate in two modes (+1st and –1st modes) that have the same threshold gain. However, the probability of single mode operation (i.e., +1st or –1st mode) depends strongly on facet reflectivity and the normalized coupling coefficient.

Complete analysis of side-by-side λ/4-phase shifted, CPM and uniform RWG DFB lasers has not been completed. However, as shown in Fig. 3 the CPM architecture effectively reduces the linewidth below 1MHz as evident in <300 kHz beat note spectrum measured for 1.5 mm long cavity using delay self heterodyne technique with a 5km fiber optical delay.

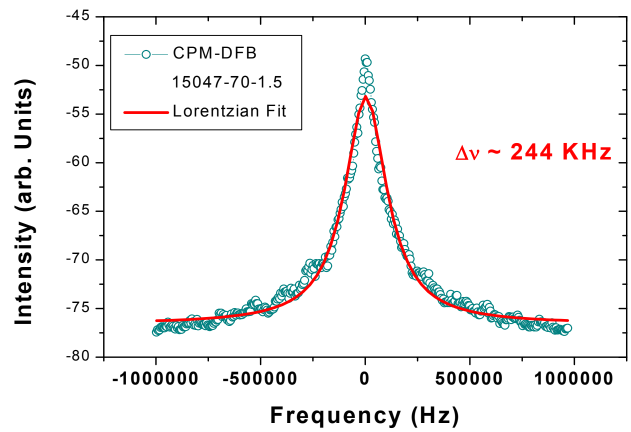


Fig.3. RF spectrum measured using delay self heterodyne technique with a 5km fiber optical delay.

Similar λ/4-phase shifted, CPM and uniform RWG DFB lasers also have been fabricated side-by-side in the 2.06-µm wavelength range. Characterization and analysis of the wavelength of the main mode (zeroth mode), neighboring submodes, and the relationship between these wavelengths and driving current I is under investigation. Additionally, linewidth, and stable single mode operation for CPM-DFB lasers in this wavelength range are yet to be determined. Preliminary results for single mode spectral characteristics along with measured pulsed mode current-power characteristics of a typical CPM 2.06-µm are shown in Fig 4 and 5 respectively.

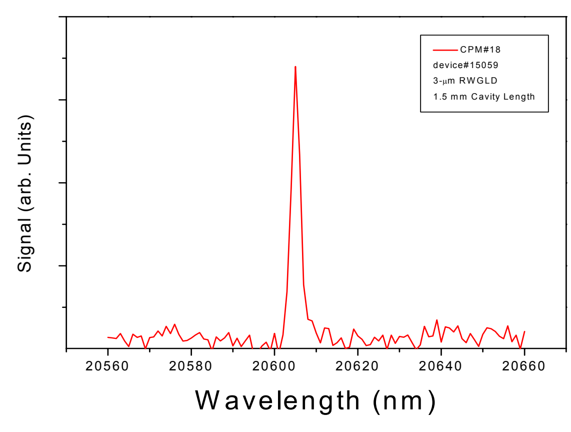


Fig. 4. Emission spectrum of a 1.500 µm long cavity 2.06 µm CPM-DFB lasers

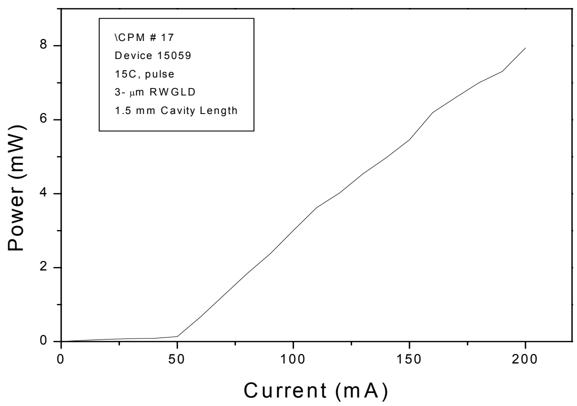


Fig.5. Pulse current-power characteristics of InGaAs/InP CPM-DFB ridge waveguide laser at 2.06-μm.

III. Sb-BASED HYBRID DEVICES

Significant progress has been made toward fabrication of single mode hybrid DBR lasers with the external Bragg grating defined on SiN waveguides deposited on a micromachined silicon bench coupled to InGaAsSb/GaSb based ridge waveguide gain chips operating in the 2-μm spectral region. Fabry-Pérot ridge waveguide lasers (gain chips) have been fabricated using wafers epitaxially grown at the MIT Lincoln Laboratory. Optical output powers in excess of 30-mW multimode at 1-kHz PRF have been achieved with the devices produced thus far. Fig. 6 shows the output spectrum of a device with a 5-μm wide, 750 μm long RWG laser along with measured pulsed mode light-current characteristics.

For efficient coupling the external waveguide is designed to have a mode similar to the Sb-based gain chip. In addition, the gain chip must be precisely aligned to the external Bragg grating waveguide. To that end, a micromachined bench provides the features facilitating vertical alignment. Lateral alignment is accomplished with a precision flip chip bonder. The top view and cross-section of the micromachined bench is provided in Fig. 7. The main feature of the bench is the precise definition of the vertical distance between stand-offs and the waveguide core. Using this technology we recently have demonstrated single mode DBR lasers operating at 650-nm [11].

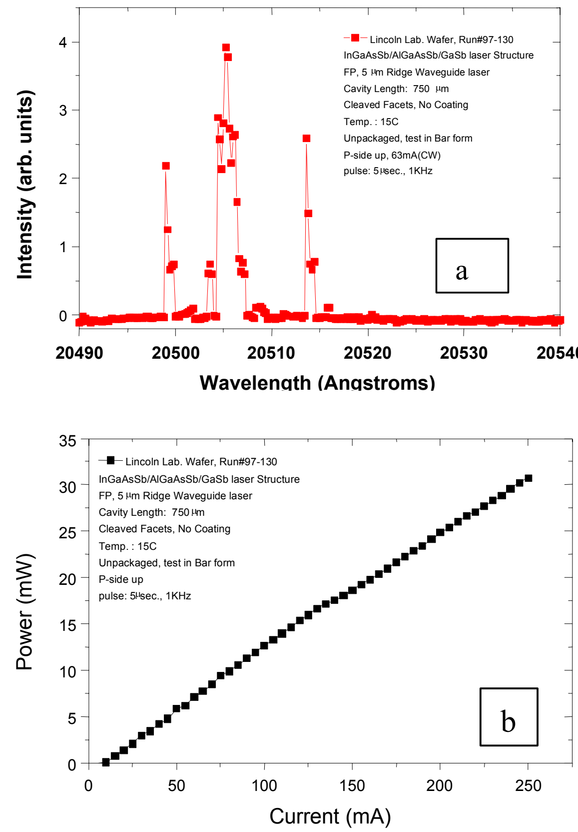
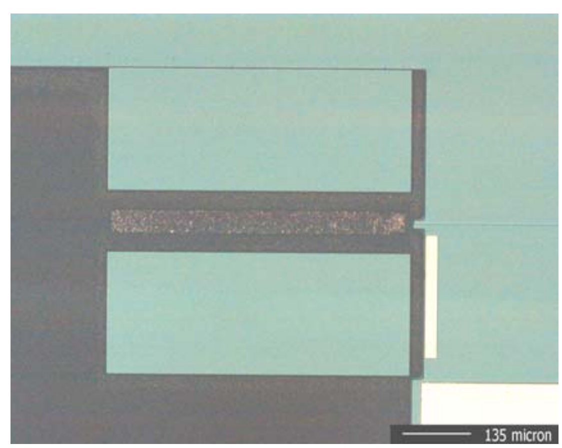


Fig. 6. (a) Emission spectrum, (b). Pulsed current-power characteristics of 5-μm ridge waveguide Fabry-Pérot lasers in InGaAsSb/AlGaAsSb/GaSb.



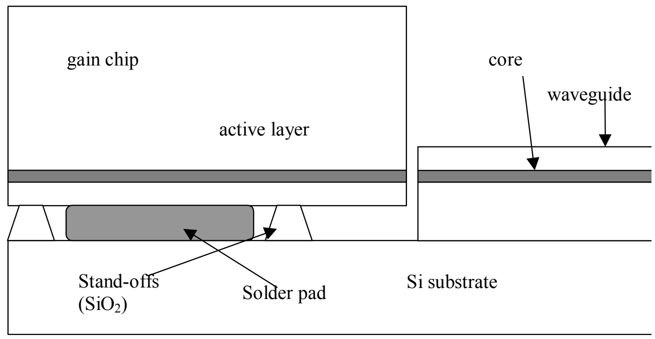


Fig. 5. The top view and cross section of the external grating waveguide micromachined bench.

IV-CONCLUSION

Corrugation Pitch-Modulation Distributed Feedback (CPM-DFB) and external grating Distributed Bragg Reflector (DBR) laser architectures are being developed to enable narrow linewidth (<500 kHz) operation of semiconductor lasers in 2-µm spectral region in laser material systems: InGaAsP/InP and AlGaAsSb/InGaAsSb/GaSb.

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